Heavy Quarkonium Spectra and its Decays in the Framework of Quark Models

Final Synopsis of the Thesis to be submitted to Mangalore University for the award of the degree of Doctor of Philosophy in Physics.

Submitted By

Praveen Prakash D'Souza P

Under the Supervisions of

Dr K B Vijayakumar

Department of Studies in Physics
Mangalore University
Mangalagangothri-574199
Mangalore,India

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Introduction

We have undertaken a microscopic study of the heavy meson spectroscopy in the framework of the constituent quark model(CQM) and calculated the masses of S, P, D and F wave heavy mesons and their decay widths in this work in the framework of CQM. The investigation of the properties of these mesons gives important information about heavy quark-antiquark interactions and heavy quark dynamics. Also, prediction of the properties of strongly interacting particles using the mesonic sector is of great importance since these particles can be easily produced in experiments and hence the theoretical predictions can be verified. Heavy mesons consist of at least one heavy quark and only a few heavy hadrons have been observed. There is a lot of activity going on in the experimental front to identify new hadrons. Hence, there is a need to compute the masses and various other properties using QCD inspired potential models. The wealth of experimental data in hadron spectroscopy would be a good testing ground for nonperturbative QCD. In recent years, the spectroscopy of hadrons containing heavy quarks has emerged from several experimental facilities such as BES, E835, CLEO, BaBar, Belle, CDF, D0, NA60 etc. All these experiments shed light on the structure and dynamics of new hadrons. Hence, the study of mass spectroscopy and decay properties of heavy quark systems becomes significant. Our Model uses the NRQM formalism for the study of properties of charmonium states using a Hamiltonian which has the heavy quark potential derived from the instanton vacuum. It is well established that the Hulthen potential model within the non-relativistic model quite successfully explains the charmonium and bottomoinum [11]. Essentially, in all phenomenological non-relativistic QCD based quark models, the Hamiltonian for the quark system consists of the kinetic energy, the two-body confinement potential and OGEP. In most of these works, it is assumed that the principal binding forces of hadrons are the long-range quark confining forces. These should be independent of quark spins and quark masses, depending just on the spatial separations of the constituent quarks. In addition, there exist short-range forces depending on the quark spins and masses. The effective short-range force stems from the one gluon exchange mechanism. The exchange of gluons can provide a binding between quarks in a hadron.

The theory encompasses different theoretical tools for understanding the interaction of elementary particles at different energy scales. The study of the hadron spectra is a fundamental and open field in theoretical physics. Since the exact form of confinement from QCD is not known, one has to go for phenomenological models in order to study the properties of hadrons. The important approaches to this subject have been: (i) Theories based on first principles such as lattice quantum chromodynamics (LQCD), (ii) QCD sum rules and (iii) Theories based on effective field theories as well as potential phenomenological models[1, 2].

The significant problem in theoretical approaches in particle physics is quark confinement wherein the isolated color charged quark is not freely available and the quarks and gluons

are permanently confined within the hadrons. In the theories based on first principles, the confinement evolves from the QCD computations. The confinement of quarks within the hadrons is assumed in the phenomenological approaches. The oldest but still effective approach is the potential models inspired by the QCD. In potential model calculations, the short distance behaviour is of the Coulomb type interaction and long-distance interactions are confinement potentials. The experimentally observed meson spectrum is compared to that predicted by theoretical models [4, 5, 6]. The discussion and interpretation are dominated by the nonrelativistic quark model, although other theoretical ideas have some bearing on particular aspects of the spectrum. Many experimental groups such as BESIII at the Beijing Electron Positron Collider (BEPC), E835 at Fermilab and CLEO at the Cornell Electron Storage Ring (CESR), the B-meson factories, BaBar at PEP-II, Belle at KEKB, the CDF and D0 experiments at Fermilab, the Selex experiment at Fermilab, ZEUS and H1 at DESY, PHENIX and STAR at RHIC, NA60 and LHCb at CERN are producing and expected to provide more precise data in upcoming experiments. The new future facility PANDA at FAIR, GSI facilities offer more significant challenges and opportunities in theoretical high energy physics. Recently, the LHCb Collaboration at LHC has realized an excellent search for baryons made with heavy quarks. Comprehensive reviews on the status of experimental heavy quarkonium physics are found in literature[13, 14, 15, 16, 17].

Aims and Objectives

In the thesis, we discuss three phenomenological models (PM). In order to study S, P, D and F wave spectra of heavy quarkonium three phenomenological non-Relativistic Quark models have been developed.

1. Non relativistic quark model with a Coulomb like potential and the linear confining potential along with the instanton potential (PM1).
2. Non relativistic quark model with Hulthen potential and linear confinement potential (PM2).
3. Non relativistic quark model with one gluon exchange potential(OGEP) and linear confinement potential (PM3).

In PM1 we have investigated the mass spectrum and decay constants of charmonium states within the framework of the NRQM by employing a Coulomb like one gluon exchange potential, linear confining potential along with the potential derived from instanton vacuum. We have predicted radiative E1, M1, two-photon, leptonic and two-gluon decay rates of low lying charmonium states.

The full $q\bar{q}$ potential used in the PM2 has a Hulthen potential and a confining linear potential. The hyperfine interaction is introduced to obtain the splittings of the spin-singlet and triplet states, while the spin-orbit and tensor interactions provide the fine structure splittings. The

model parameters and the wave function that reproduce the mass spectra are used to investigate the decay properties of B and B_s mesons.

In PM 3, meson properties are investigated in a model consisting of a non-relativistic confinement potential. The quark-antiquark interaction potential is given by the OGEP. The OGEP also provides the spin-dependent interactions leading to hyperfine and fine structure splittings. The non-relativistic with OGEP has been successful in predicting the D and D_s meson spectra, decay constants and radiative decay widths.

Methodology

Non relativistic quark model (PM1)

In a potential model approach the entire dynamics of quarks in a meson is governed by the Hamiltonian which has kinetic energy term (K) and potential energy (V),

$$H = K + V. \tag{0.0.1}$$

Where,

$$K = M + \frac{p^2}{2\mu} \tag{0.0.2}$$

Here p is the relative momentum, $\mu = \frac{m_Q m_{\bar{Q}}}{m_Q + m_{\bar{Q}}}$ is the reduced mass of the $Q\bar{Q}$ system, where m_Q and $m_{\bar{Q}}$ are the masses of the individual quark and anti quark respectively and M is the total mass of quark and antiquark [12]. The potential energy V is the sum of the heavy-quark potential $V_{Q\bar{Q}}(\vec{r})$,confining potential $V_{conf}(\vec{r})$ and Coulomb potential $V_{coul}(\vec{r})$,

$$V(\vec{r}) = V_{Q\bar{Q}}(\vec{r}) + V_{coul}(\vec{r}) + V_{conf}(\vec{r}) \tag{0.0.3}$$

The $V_{Q\bar{Q}}(\vec{r})$ is,

$$V_{Q\bar{Q}}(\vec{r}) = V_C(\vec{r}) + V_{SD}(\vec{r}). \tag{0.0.4}$$

Here $V_C(\vec{r})$ and $V_{SD}(\vec{r})$ are the central and spin dependent potentials due to instanton vacuum $V_C(\vec{r})$ [18].

$$V_C(\vec{r}) \simeq \frac{4\pi\bar{\rho}^3}{\bar{R}^4 N_c}\left(1.345\frac{r^2}{\bar{\rho}^2} - 0.501\frac{r^4}{\bar{\rho}^4}\right) \tag{0.0.5}$$

Here, $\bar{\rho} = \frac{1}{3}$ fm is the average size of the instanton, $\bar{R} = 1$ fm is the average separation between instantons and N_C is the number of colors which is 3. The spin-spin interaction $V_{SS}(\vec{r})$, the spin-orbit term $V_{LS}(\vec{r})$ and the tensor term $V_T(\vec{r})$ constitute the spin dependent potential $V_{SD}(\vec{r})$; The $V_{SD}(\vec{r})$ is,

$$V_{SD}(\vec{r}) = V_{SS}(\vec{r}) + V_{LS}(\vec{r}) + V_T(\vec{r}) \tag{0.0.6}$$

Where,

$$V_{SS}(\vec{r}) = \frac{1}{3{m_Q}^2}\nabla^2 V_C(\vec{r});\ V_{LS}(\vec{r}) = \frac{1}{2{m_Q}^2}\frac{1}{r}\frac{dV_C(\vec{r})}{dr};$$
$$V_T(\vec{r}) = \frac{1}{3{m_Q}^2}\left(\frac{1}{r}\frac{dV_C(\vec{r})}{dr} - \frac{d^2V_C(\vec{r})}{dr^2}\right). \tag{0.0.7}$$

The coulomb-like (perturbative) one gluon exchange part of the potential is given by

$$V_{coul}(\vec{r}) = \frac{-4\alpha_s}{3r} \tag{0.0.8}$$

where α_s is the strong coupling constant and r is the inter quark distance.

The confinement term represents the non perturbative effect of QCD which includes the spin-independent linear confinement potential [12].

$$V_{conf}(\vec{r}) = -\left[\frac{3}{4}V_0 + \frac{3}{4}cr\right]F_1{\cdot}F_2 \tag{0.0.9}$$

where c and V_0 are constants. F is related to the Gell-Mann matrix, $F_1 = \frac{\lambda_1}{2}$ and $F_2 = \frac{\lambda_2}{2}$ and $F_1{\cdot}F_2 = \frac{-4}{3}$ for the mesons.

Non relativistic quark model (PM2)

The Hamiltonian used in PM 2 has the form ,

$$H = M + \frac{p^2}{2\mu} + V(r), \tag{0.0.10}$$

where p is the relative momentum, μ is the reduced mass of the $Q\bar{Q}$ system and $V(r)$ is the $Q\bar{Q}$ interaction potential. $M = m_Q + m_{\bar{Q}}$ and $\mu = \frac{m_Q m_{\bar{Q}}}{m_Q + m_{\bar{Q}}}$, where m_Q and $m_{\bar{Q}}$ are the masses of the individual quark and antiquark respectively. The central potential $V(r)$ is of the form,

$$V(r) = V_H(r) + V_C(r) + V_0, \tag{0.0.11}$$

where V_H is the Hulthen potential [19],

$$V_H(r) = -\mu_0\frac{\exp(-r/\mu)}{1-\exp(-r/\mu)}, \tag{0.0.12}$$

μ_0 is a constant and μ is the screening parameter, which determines the range for the Hulthen potential. In the limit $r \to 0$, the potential (0.0.12), behaves like the Coulomb potential: $V_H(r) \to -\mu_o\mu/r$. Thus the Hulthen potential $V_H(r)$ may be treated as a screened Coulomb potential, with a screening parameter μ. In the limit $r \to \infty$, $V_H(r)$ tends to zero. The confinement potential V_C is given by a linear expression in r, as suggested by the lattice QCD calculations,

$$V_C(r) = cr, \tag{0.0.13}$$

where c is a constant.

Non relativistic quark model (PM3)

The Hamiltonian employed in our model includes kinetic energy part, confinement potential and OGEP [20].

$$H = K + V_{CONF} + V_{OGEP} \tag{0.0.14}$$

The kinetic energy part (K) is the sum of the kinetic energies including the rest mass minus the kinetic energy of the center of mass motion (CM) of the total system, i.e.,

$$K = \left[\sum_{i=1}^{2} M_i + \frac{P_i^2}{2M_i}\right] - K_{\rm cm}, \tag{0.0.15}$$

with M_i and P_i as the mass and momentum of the ith quark, respectively. K_{CM} is the kinetic energy of the centre of mass motion.

The confinement potential must come ultimately from a non-perturbative treatment of QCD, whereas the residual interaction OGEP is based on perturbation theory. In phenomenological quark models the confinement potential is assumed to be harmonic oscillator potential ($V \sim r^2$) or logarithmic potential ($V \sim ln(r)$) or linear potential ($V \sim r$). In PM2 we have chosen the linear potential which represents the non perturbative effect of QCD that confines quarks within the color singlet system [21].

$$V_{CONF}(\vec{r}_{ij}) = -a_c r_{ij} \vec{\lambda}_i \cdot \vec{\lambda}_j \tag{0.0.16}$$

where a_c is the confinement strength and λ_i and λ_j are the generators of the color SU(3) group for the ith and jth quarks.It should be noted that the two body confinement potential, has symmetric and antisymmetric terms.

$$V_{so}^{conf} = \sum_{i>j} -\frac{1}{4m^2 r_{ij}} \frac{dV^{conf}}{dr_{ij}} \{(r_{ij} \times p_{ij}) \cdot (\sigma_i + \sigma_j) + [r_{ij} \times (p_i + p_j)/2] \cdot (\sigma_i - \sigma_j)\} \tag{0.0.17}$$

If one includes both the symmetric and antisymmetric terms the two terms of V_{ij}^{conf} cancel each other and give an almost vanishing contribution to the single baryon/meson spectra. Also, it should be noted that the symmetric term of the V_{ij}^{conf} has opposite sign to the one in V_{ij}^{OGEP} and hence cancels the contribution from the symmetric term of V_{ij}^{conf} in single baryon/meson system. The antisymmetric term is Galilei non-invariant and hence is not considered for calculations. In our calculation we use OGEP and a purely linear confinement potential. The OGEP is given by

$$V_{OGEP} = V_{OGEP}^{CENTRAL}(\vec{r}) + V_{OGEP}^{SO}(\vec{r}) + V_{OGEP}^{ten}(\vec{r}) \tag{0.0.18}$$

The central part of OGEP is,

$$V_{OGEP}(\vec{r}) = \frac{\alpha_s}{4} \vec{\lambda}_i \cdot \vec{\lambda}_j \left[\frac{1}{r_{ij}} - \frac{\pi}{M_i M_j} \left(\frac{M_i}{M_j} + \frac{M_j}{M_i} + \frac{2}{3} \vec{\sigma}_i \cdot \vec{\sigma}_j\right) \delta(\vec{r}\right] \tag{0.0.19}$$

where the first term represents the residual Coulomb energy and the second term is the chromo-magnetic interaction leading to the hyperfine splitting. σ_i is the Pauli spin operator and α_s is the quark-gluon coupling constant.

The non−central part of OGEP has the spin−orbit interaction $V^{SO}_{OGEP}(\vec{r})$ and tensor term $V^{ten}_{OGEP}(\vec{r})$. The spin-orbit interaction of OGEP is given by,

$$V^{SO}_{OGEP}(\vec{r}) = -\frac{\alpha_s}{4}\lambda_{\mathbf{i}} \cdot \lambda_{\mathbf{j}} \left[\frac{3}{8M_iM_j}\frac{1}{r^3}(\vec{r}\times\vec{p})\cdot(\sigma_{\mathbf{i}}+\sigma_j)\right] \tag{0.0.20}$$

where the relative angular momentum is defined as in terms of relative position $\vec{r}$ and the relative momentum $\vec{p}$. Unlike the tensor force, the spin−orbit force does not mix states of different $\vec{L}$, since L^2 commutes with $\vec{L}\cdot\vec{S}$, $\vec{L}$ is still a constant of motion, but L_z is not.

The tensor potential is

$$V^{ten}_{OGEP}(\vec{r}) = -\frac{\alpha_s}{4}\lambda_{\mathbf{i}} \cdot \lambda_{\mathbf{j}} \left[\frac{1}{4M_iM_j}\frac{1}{r^3}\right] \hat{S}_{ij} \tag{0.0.21}$$

where,

$$\hat{S}_{ij} = [3(\vec{\sigma}_i\cdot\hat{r})(\vec{\sigma}_j\cdot\hat{r}) - \vec{\sigma}_i\cdot\vec{\sigma}_j] \tag{0.0.22}$$

The tensor potential is a scalar which is obtained by contracting two second rank tensors. Here, $\hat{r} = \hat{r}_i - \hat{r}_j$ is the unit vector in the direction of $\vec{r}$. In the presence of the tensor interaction, $\vec{L}$ is no longer a good quantum number.

Results and Discussions

In PM1,PM2 and PM3 we have used the harmonic oscillator wave function which has been extensively used in atomic and nuclear physics as the trial wave function for obtaining the $Q\bar{Q}$ mass spectrum. The harmonic oscillator wave function has been used successfully for the prediction of light meson spectrum. The harmonic oscillator wave function is given by:

$$\Psi_{nlm}(r,\theta,\phi) = N\left(\frac{r}{b}\right)^l L_n^{l+\frac{1}{2}}(r^2/b^2)\exp(-r^2/b^2)\ Y_{lm}(\theta,\phi), \tag{0.0.23}$$

where N is the normalization constant,

$$|N|^2 = \frac{2\ n!}{b^3\pi^{\frac{1}{2}}}\frac{2^{(2(n+l)+1)}}{(2n+2l+1)!}(n+l)!, \tag{0.0.24}$$

and $L_n^{l+\frac{1}{2}}(x)$ are the associated Laguerre polynomials.

Study of hadronic decay properties is another equally important area of research in the field of hadron physics. The experimental detection of heavy mesons has opened up a vast data

bank for the hadronic decays into various channels. A hadronic transition or decay between heavy quark meson levels can be understood as a two-step process in which gluons first are emitted from heavy quarks annihilating each other and then recombine into light hadrons. Perturbative QCD is not directly applicable because the energy available to the light hadrons is small, and the emitted gluons are soft. Nevertheless, the final heavy quark meson state is small compared to the system of light hadrons and moves nonrelativistically in the rest frame of the decaying heavy quark meson state.

In PM1 we have obtained the spectrum and decay rates of charmonium states within the framework of the NRQM by employing a Coulomb like potential from the perturbative one gluon exchange and the linear confining potential along with the potential derived from instanton vacuum to account for the hyperfine mass splitting of charmonium states in variational approach. The contribution of the instanton to the mass spectrum of charmonium is quite significant. We calculated radiative E1, M1, two-photon, leptonic and two-gluon decay rates of low lying charmonium states. A very good agreement is obtained with the experimental masses and decay widths for all the states. The estimated branching ratio of two gluons decaying into light hadrons is in good agreement with experimental and lattice results. Below the open charm threshold, the theoretically calculated masses are in agreement with lattice calculations and with experimental results. The calculations demonstrate that the charmonium masses/mass splittings can be obtained with a combination of Coulombic, instanton and confinement potentials. Hence, in the heavy quark sector, the instanton potential plays the role of OGEP in PM1. The contribution of the central part of the instanton potential to the masses of the charmonium states is significant.

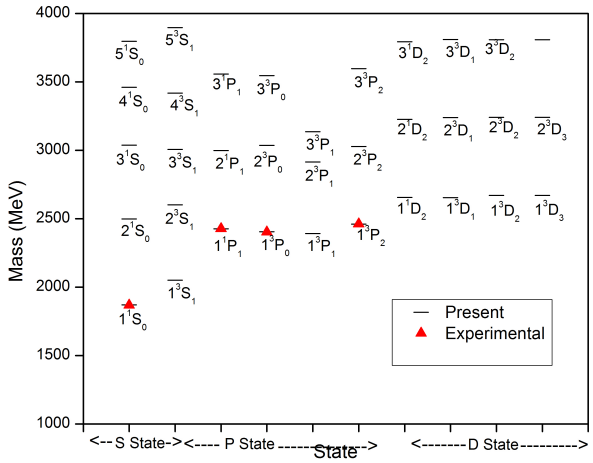

Figure 1: Mass spectrum of the D Meson

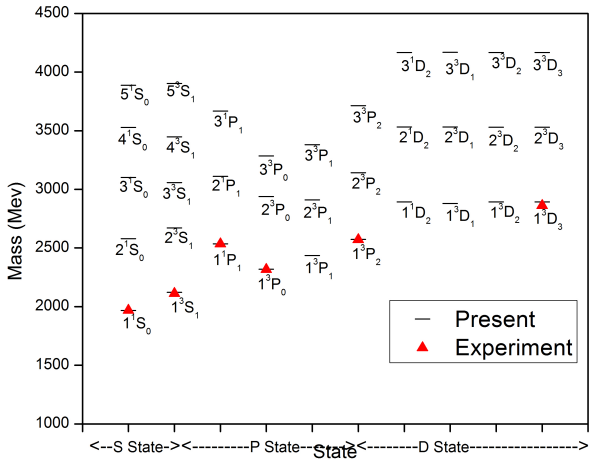

Figure 2: Mass spectrum of the D_s Meson

In PM2, meson properties were investigated in a NRQM consisting of a Hulthen potential and a confining linear potential. In PM2, the screening of the short distance quark-antiquark potential has been taken into account. This is achieved through the inclusion of the Hulthen potential. The Hulthen potential can be thought of as a screened Coulomb potential. The mass

spectrum was obtained variationally, and the model parameters and the wave function that reproduce the mass spectra were used to investigate the decay properties of B and B_s mesons. The spectra obtained for both B and B_s agree with the experimental results and with the theoretical predictions from other models. In PM2, we have obtained mass and decay widths of B and B_s mesons. By using wave function at the origin, we have obtained the pseudoscalar decay constants of B and B_s mesons with and without QCD corrections.

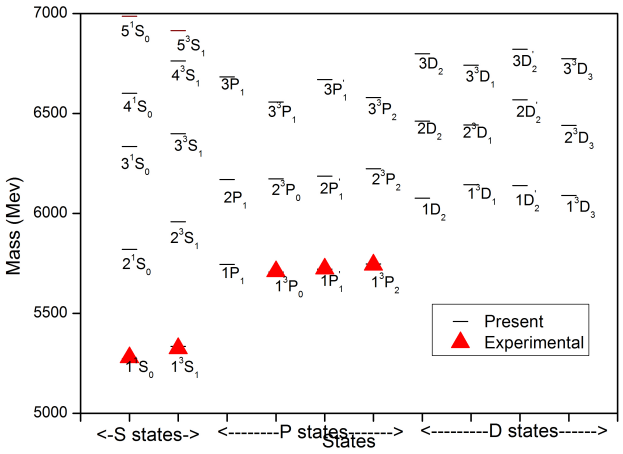

Figure 3: Mass spectrum of the B Meson

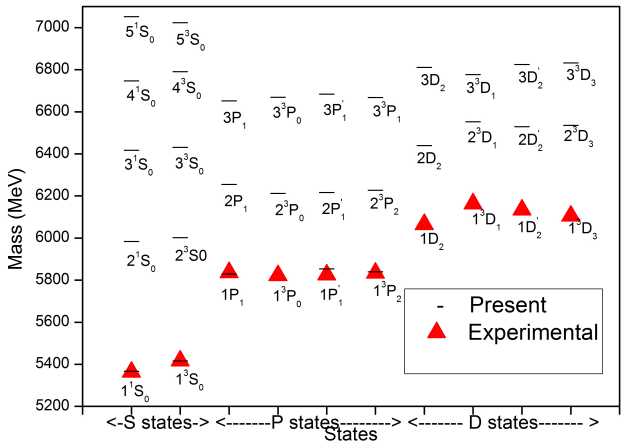

Figure 4: Mass spectrum of the B_s Meson

In PM3, meson properties were obtained in a nonrelativistic model consisting of OGEP and linear confinement potential. The OGEP provides the spin-dependent interactions leading to hyperfine splittings. The OGEP was successful in predicting the light meson spectra. Hence in this work, we have studied the mass spectra and decay properties of D and D_s mesons. We have obtained the centre of mass and the spin average masses of D and D_s mesons. The results show that PM3 gives a satisfactory description of both D and D_s meson spectra. The observed spin-singlet states are reasonably in good agreement with the experimental results.

Outlines of the Thesis

The heavy quarkonia are the most powerful systems for understanding the heavy quark-antiquark interactions in QCD. As explained in the previous section, there are many ways in which these systems are studied. The oldest but still consistent approach is the potential model wherein the widely accepted potential for the interaction between constituent quarks is the Cornell potential. Chapter 1 gives brief introduction to QCD and elementary particle physics. In Chapter 2, we discuss three phenomenological potential models. In chapter 3, we compute the mass spectra of η_c, J/ψ, B, B_s, D, D_s. For computing the spectra, we employed the nonrelativistic approach. For computing the masses of excited states; we relevant spin-orbit and tensor terms. We have

computed the various decay properties such as leptonic decay constants, annihilation widths and electromagnetic transition widths. We have compared our findings with the available experimental data and with other theoretical models. In chapter 3, we have computed the mass spectra and decay properties of heavy quarkonia by considering the nonrelativistic treatment for heavy hadrons and we have made a qualitative comparison of the three models. Finally, in chapter 4, the summary and conclusions are given. We have also discussed the future prospects of the present work.

Bibliography

[1] A. De Rujula, Howard Georgi, and S. L. Glashow. Phys.Rev. D, 12:147–162, (1975).

[2] R.K. Bhaduri, L.E. Cohler, and Y. Nogami. Il Nuovo Cimento A 65(3):376–390, (1981).

[3] K. B. Vijaya Kumar, Bhaghyesh, and A. P. Monteiro. Indian Journal of Physics, 87(5):493, (2013).

[4] A. P. Monteiro, K. B. Vijaya Kumar, and Bhaghyesh. Indian Journal of Pure and Applied Physics, 52:369, (2014).

[5] Antony Prakash Monteiro, K. B. Vijaya Kumar, and Bhaghyesh. Communications in Theoretical Physics, 56(3):476, (2011).

[6] Bhaghyesh, K. B. Vijaya Kumar, and Yong-Liang Ma. International Journal of Modern Physics A, 27(03n04):1250011, (2012).

[7] U. T. Yakhshiev, H.-C. Kim, M. M. Musakhanov, E. Hiyama and B. Turimov, Chin.Phys. C41 083102 (2017).

[8] K. B. Vijaya Kumar, B. Hanumaiah, and S.Pepin, Eur.Phys. J A 19, 247 (2004).

[9] Bhavyashri, S. Sarangi, G. Saldanha, and K. B. Vijaya Kumar, Pramana J. Phys. 70, 75, (2008).

[10] K. B. Vijaya Kumar et al., Int. J. Mod. Phys. A 22, 4209(2009).

[11] Bhaghyesh, K. B. Vijaya Kumar and Antony Prakash Monteiro J. Phys. G: Nucl. Part. Phys. 38 085001(2011).

[12] Bhaghyesh and K. B. Vijaya Kumar, International Journal of Modern Physics A 27 1250127 (2012).

[13] R. Aaij et al (LHCb Collaboration), Phys. Lett. B, 707: 52 (2012).

[14] R. Aaij et al (LHCb Collaboration), JHEP, 1706: 047 (2017).

[15] V. Khachatryan et al. (CMS Collaboration), JHEP, 1409: 094 (2014).

[16] M. Aaboud et al. (ATLAS Collaboration), Eur. Phys. J. C,77: 76 (2017).

[17] K. Abe et al. (Belle Collaboration), Phys. Rev. Lett., 89:142001 (2002).

[18] U. T. Yakhshiev, H.-C. Kim, M. M. Musakhanov, E. Hiyama and B. Turimov, Chin.Phys. C41 083102(2017).

[19] L. Hulthen, Ark. Mat. Astron. Fys. A 28, 5 (1942).

[20] B. Silvestre-Brac and C. Gignoux, Phys. Rev. D 32, 743 (1985).

[21] A. P. Monteiro, M. Bhat and K. B. Vijaya Kumar, International Journal of Modern Physics A 32 1750021(2017).

[22] Antony Prakash Monteiro, Manjunath Bhat, and K. B. Vijaya Kumar Phys. Rev. D 95, 054016 (2017).

[23] Antony Prakash Monteiro, Manjunath Bhat, and K. B. Vijaya Kumar International Journal of Modern Physics A 1750021 (2017).

[24] Manjunath Bhat, Antony Prakash Monteiro, and K. B. Vijaya Kumar International Journal of Modern Physics A 1750037 (2017).

List of Publications

In Journals

1. *Properties of Charmonium States in a Phenomenological Approach*, **Praveen P. D'Souza**, A. P. Monteiro and K. B. Vijaya Kumar Communications in Theoretical Physics **71(2)**, 192 (2019).

2. *Introduction to Elementary Particles*,Antony Prakash Monteiro **Praveen P. D'Souza**, PEARL Multidisciplinary Journal 2017(3)91-142.

3. *Properties of B and B_s Mesons States in a Non-relativistic Quark Model with the inclusion of coupled channel effects* **Praveen P. D'Souza**, A. P. Monteiro and K. B. Vijaya Kumar. Communicated to Phys.Rev.D

4. *Mass Spectra and Decay Properties of D and D_s Mesons States in a Non-relativistic Quark Model* -**Praveen P. D'Souza**, A. P. Monteiro and K. B. Vijaya Kumar. Communicated to International Journal to Modern Physics A.

In Conferences

1. Instanton Contribution to the charmonium Mass spectra by **Praveen P. DSouza**, A. P. Monteiro, K. B. Vijay Kumar, Proceedings of the DAE International Symp. on Nucl. Phys. 63 (2018) (December 10-14, 2018 Bhabha Atomic Research Centre, Mumbai-400 085, India)

2. Hadron Loop effects on B Meson Masses in a Non-Relativistic Quark Model by **Praveen P. DSouza**, A. P. Monteiro, K. B. Vijay Kumar, Vipin Naik N S, Proceedings of the DAE International Symp. on Nucl. Phys. 63 (2018) (December 10-14, 2018 Bhabha Atomic Research Centre, Mumbai-400 085, India)

3. Estimating the Branching Ratio for the Charmonium: Two gluon decay, K. B. Vijay Kumar, A. P. Monteiro, **Praveen P.DSouza**, Proceedings of the DAE International Symp. on Nucl. Phys. 63 (2018) (December 10-14, 2018 Bhabha Atomic Research Centre, Mumbai-400 085, India)

4. Mass Spectrum of low lying Bottomonium states in a Non-Relativistic Quark Model with Yukawa Potential by A.P Monteiro, **Praveen P DSouza**, Vidyalakshmi N, K.B Vijayakumar, Proceedings of the DAE International Symp. on Nucl. Phys. 63 (2018) (December 10-14, 2018 Bhabha Atomic Research Centre, Mumbai-400 085, India)

5. Mass Spectrum of Low lying Charmonium Spectrum in a Non-relativistic Quark Model with Woods-Saxon Potential by A.P Monteiro, **Praveen P DSouza**, Navya G.R., K.B Vijayakumar, Proceedings of the DAE International Symp. on Nucl. Phys. 63 (2018) (December 10-14, 2018 Bhabha Atomic Research Centre, Mumbai-400 085, India)

6. Effects of Coupled Channels in Charmonium Masses with Instanton Potential by A.P Monteiro, **Praveen P DSouza**, K. B. Vijay Kumar, Proceedings of the DAE International Symp. on Nucl. Phys. 63 (2018) (December 10-14, 2018 Bhabha Atomic Research Centre, Mumbai-400 085, India)

7. Mass shift in B_s Meson Spectrum with Hadronic Loop Effects by K. B. Vijaya Kumar, A. P. Monteiro, Vipin Naik N S, **Praveen P.DSouza**, Proceedings of the DAE International Symp. on Nucl. Phys. 63 (2018) (December 10-14, 2018 Bhabha Atomic Research Centre, Mumbai-400 085, India)

8. Hadronic Loop Effects in D_s Meson Mass Spectrum by A.P Monteiro, Vipin Naik N S, K. B. Vijay Kumar, **Praveen P. DSouza**, E. Deepak DSilva, Proceedings of the DAE International Symp. on Nucl. Phys. 63 (2018) (December 10-14, 2018 Bhabha Atomic Research Centre, Mumbai-400 085, India)

9. Mass spectrum of D_s Meson is a Non-Relativistic Quark Model with Hulthen Potential by E. Deepak DSilva, A.P Monteiro,**Praveen P. DSouza**, Vipin Naik N S and K. B. Vijaya Kumar, Proceedings of the DAE International Symp. on Nucl. Phys. 63 (2018) (December 10-14, 2018 Bhabha Atomic Research Centre, Mumbai-400 085, India)

10. Mass spectrum of Orbitally Excited States of B Mesons in a Non-Relativistic Quark Model with Hulthen Potential,**Praveen P D'Souza**, Antony Prakash Monteiro, K.B Vijaya Kumar, Proceedings of the DAE International Symp. on Nucl. Phys. 62, (2017) (December 20-24, Thapar University, Patiala)

11. Mass spectrum of Orbitally Excited Charmonium in a Non-Relativistic Quark model with an Instanton Potential,**Praveen P D'Souza**, Antony Prakash Monteiro, K.B Vijaya Kumar, Proceedings of the DAE International Symp. on Nucl. Phys. 62, (2017) (December 20-24, Thapar University, Patiala

12. A Green's Function Approach to the Non-Relativistic Wave Equation with Hulthen Potential,**Praveen P D'Souza**, Antony Prakash Monteiro, K.B Vijaya Kumar, Proceedings of the DAE International Symp. on Nucl. Phys. 62, (2017) (December 20-24, Thapar University, Patiala)

13. Radiative Transitions of B and B_s Mesons in a Non-Relativistic Quark Model with Hulthen Potential,**Praveen P D'Souza**, Antony Prakash Monteiro, K.B Vijaya Kumar, Proceedings of the DAE International Symp. on Nucl. Phys. 62, (2017) (December 20-24, Thapar University, Patiala)

14. Radiative Decays of Charmonium In a Non-Relativistic Quark Model with an Instanton Potential, Antony Prakash Monteiro,**Praveen P D'Souza**, K.B Vijaya Kumar, Proceedings of the DAE International Symp. on Nucl. Phys. 62, (2017) (December 20-24, Thapar University, Patiala)

15. Mass Spectrum of Orbitally Excited B_s Mesons in a Non-Relativistic Quark Model with Hulthen Potential, Antony Prakash Monteiro,**Praveen P D'Souza**, K.B Vijaya Kumar,

Proceedings of the DAE International Symp. on Nucl. Phys. 62, (2017) (December 20-24, Thapar University, Patiala)

16. Annihilation Decays of Charmonium in a Non-Relativistic Quark Model with an Instanton Potential, K.B Vijaya Kumar,**Praveen P D'Souza**, Antony Prakash Monteiro, Proceedings of the DAE International Symp. on Nucl. Phys. 62, (2017) (December 20-24, Thapar University, Patiala)

17. S-wave Masses of B Meson in a Non-relativistic Quark Model with Hulthen Potential, **Praveen P D'Souza**, Antony Prakash Monteiro, Manjunath Bhat, K. B Vijayakumar, Proceedings of the DAE International Symp. on Nucl. Phys. 61, (2016) (December 05-09, Saha Institute of Nuclear Physics, Kolkata)

18. Realistic Results of Low-Lying Charmonium Masses Using Instanton Potential, **Praveen P D'Souza**, Antony Prakash Monteiro, Manjunath Bhat, K. B VijayakumarProceedings of the DAE International Symp.on Nucl. Phys. 61, (2016) (December 05-09, Saha Institute of Nuclear Physics, Kolkata)

19. Ground State Charmed Meson Spectra in a Non-Relativistic Quark Model, Antony Prakash Monteiro, Manjunath Bhat,**Praveen P D'Souza**, K.B. Vijaya Kumar, Proceedings of the DAE International Symp. on Nucl. Phys. 61, (2016) (December 05-09, Saha Institute of Nuclear Physics, Kolkata)

20. Annihilation decays of bottomonium, Antony Prakash Monteiro, Manjunath Bhat, **Praveen P D'Souza**, K.B Vijaya Kumar, Proceedings of the DAE International Symp. on Nucl. Phys.61,(2016) (December 05-09, Saha Institute of Nuclear Physics, Kolkata)

Praveen Prakash D'Souza P
PhD Candidate

Dr K B Vijayakumar
Professor
Department of Studies in Physics
Mangalore University,
Mangalagangotri

Mangalagangothri
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